

**FINAL REPORT**

**TRIAL USE OF A STAINLESS STEEL-CLAD STEEL BAR  
IN A NEW CONCRETE BRIDGE DECK IN VIRGINIA**

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## **ABSTRACT**

As part of the Virginia Transportation Research Council's effort to identify cost-effective, corrosion-resistant reinforcing bars that can be used in concrete bridges exposed to heavy salting, a 316L stainless steel-clad bar was tested in a new bridge deck under the Innovative Bridge Research and Construction Program sponsored by the Federal Highway Administration.

This field project was aimed at supplementing a laboratory evaluation that confirmed the excellent corrosion resistance of this potentially cost-effective material. The project revealed no significant technical problem with substituting this type of bar for the black steel and epoxy-coated bars currently used. A life-cycle cost analysis indicated that, even though the initial cost of the clad bars is slightly higher, the long-term cost is lower and the service life expectancy of the structure increases.

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## **INTRODUCTION**

In the past, concrete bridges were built with black steel reinforcing bars and a thin layer of concrete over the top mat of the bars. In states where deicing salts are used during icy winter storms, such a combination led to premature concrete damage in many concrete bridges, often as early as a few years after their construction. This soon led to the recognition by many that this costly problem is caused by the accumulation of a sufficient amount of chloride ions, from the deicing salts, in the concrete to initiate corrosion of the steel bars. With this knowledge, two important measures were adopted by state highway agencies in the late 1970s to early 1980s in building new concrete bridges. These measures, which included the use of epoxy-coated bars and the use of a thicker concrete cover over the bars, have led to delays in the onset of bar corrosion in many of the concrete bridges built since then so that the majority of these bridges will likely reach their 50-year design life. The recent adoption of new specifications for relatively less permeable concrete would further ensure that newer concrete bridges would last even longer, perhaps exceeding this design life.

However, many state highway agencies are now faced with even more serious financial problems, as available funds are becoming increasingly disproportionate with respect to the needs for maintenance and replacement of existing highway infrastructure assets and construction costs are spiraling upward—by 12 percent annually since 1987. It is now even more incumbent on highway engineers to do all that is possible to stretch the available funds, including designing and building a highway infrastructure that will last longer. To their credit, bridge engineers at the state and federal levels, have adopted longer design life goals of 75 and 100 years for minor and major concrete bridges, respectively, without a major repair. A new reinforcing bar that is corrosion resistant and durable enough to tolerate the rough handling that is common in construction sites and inexpensive can be very valuable in ensuring that this challenge will be met. The use of such a bar, in addition to the other beneficial measures

mentioned earlier, would be prudent—especially when the risk of concrete cracking occurring in new concrete bridge decks, often soon after construction, still exists.

### **Use of Stainless Steel in Reinforcing Bars**

Stainless steels, which are iron alloys containing a minimum of approximately 11 percent chromium, have long been widely used as construction materials for key equipment in most of the major industries because they combine good mechanical properties with good corrosion resistance.<sup>1</sup> Their use in infrastructures has been a different story, even though its merit has been suggested as early as 1985. Zoob et al. reported that testing of reinforcing bars made of type 304 austenitic stainless steel exhibited no macrocell corrosion current, even when the total chloride in the concrete slabs were as high as 5.5 kg/m<sup>3</sup>, about 7 to 10 times the corrosion threshold for conventional black bar.<sup>2</sup> Following this, an intensive study on black steel, galvanized steel, types 405 and 430 ferritic stainless steels, and types 302, 315, and 316 austenitic stainless steels was conducted by Treadaway et al.<sup>3</sup> These investigators reported that none of the concrete specimens with the austenitic stainless steel bars exhibited corrosion-induced cracks after 10 years of exposure, while the concrete specimens reinforced with all the other materials cracked, although the two ferritic stainless steels were able to withstand chloride up to 1 percent.<sup>3</sup> In another study in concrete, Gu et al. reported that the corrosion rate of Nitronic 33 stainless steel was at least 50 times lower than that of black steel, both after a 2-year exposure in chloride contaminated concrete.<sup>4</sup>

These investigations provided convincing proofs of the merit of some of these stainless steels as corrosion-resistant reinforcing bars. In addition, since the mechanical properties of many stainless steels are similar to steels of high yield strengths, their use in concrete structures should not present any practical difficulties. However, these advantages notwithstanding, the use of stainless steels as reinforcement in new concrete bridges has been very limited mainly because of the high cost of stainless steel bars, with installed price of about \$5.06/kg (\$2.30/lb) compared to \$1.10/kg (\$0.50/lb) for carbon steel bars. From 1985 to 1998, there were approximately 11 known applications of stainless steels in North America and Europe in infrastructure, including bridge decks, barrier walls, ramps, columns, beams, and road slabs.<sup>5</sup> In these applications, only five grades of stainless steels (304, 316, 304L, and 316L austenitic, and 2205 duplex) have been used because they provide the desirable combination of corrosion resistance, price, and availability.

Fortunately, among the four materials tested by Rasheeduzzafar et al. was a black bar clad with a layer of type 304 stainless steel, which is a general-purpose grade that is widely used in applications requiring a good combination of corrosion resistance and formability.<sup>6</sup> In that investigation, concrete beams constructed with bare mild, galvanized, epoxy-coated, and 304-clad reinforcing steel and containing three different levels of chloride, were exposed for 7 years in the coastal flats of the Arabian Gulf, an area characterized by extremely warm, humid, and salty air. Rasheeduzzafar et al. reported in 1992 that, after the 7-year exposure, the stainless steel-clad reinforcing bars had no sign of corrosion whereas concrete beams containing the other bars cracked in 65 to 172 days. From their data, it was estimated that the stainless steel-clad bar

lasted at least 39 times longer than bare black steel, 15 times longer than galvanized steel, and 16 times longer than epoxy-coated steel bars.<sup>6</sup>

Then in 1996, as the first part of a 5-year investigation sponsored by the Federal Highway Administration (FHWA) to search for the “next-generation” reinforcing bars, McDonald et al. tested a 304 stainless steel-clad bar and 19 other bars (including several solid stainless steels and several other types of clad bars that were still in the developmental stage).<sup>7</sup> These investigators reported that, when subjected to accelerated cyclic wetting and drying tests in two corrosive solutions, the corrosion rate of the stainless steel-clad steel bar and the solid stainless steel bar was (1) approximately 1,000 times less when all were tested in a 3% NaCl solution, and (2) approximately 100 times less in a high-pH solution of 0.3N KOH + 0.05N NaOH + 3% NaCl.<sup>7</sup>

The results of the last two laboratory studies suggested that by cladding the corrosion-susceptible black steel with a thin outer layer of a corrosion-resistant stainless steel, the resulting composite bar would have a corrosion resistance comparable to those of stainless steels but without the high price of the solid stainless steel bars. Although the initial cost of solid stainless steel bars can be almost 5 times that of carbon steel (black) bars, stainless steel-clad bars can be produced and marketed for as low as \$1.43/kg (\$0.65/lb), or only 2.6 times that of black bars. Therefore, stainless steel-clad bars represent a potentially cost-effective alternative to solid stainless steel bars for ensuring that future concrete bridges will have a long life expectancy. This approach of protecting the carbon steel with an outer layer of stainless steel is essentially the same as protecting carbon steel bars with a layer of epoxy coating, as in epoxy-coated bars; except in this case, the stainless steel clad is significantly more resistant to abrasion and impact damages than the epoxy coating used in the coated bars.

### **Stainless Steel-Clad Steel Bar: A Potentially Effective Corrosion Protection System**

Although stainless steel-clad bars have been sold in Europe since the mid 1980s, their availability in commercial quantities had not been reliable. In fact, the material was eliminated from further evaluation in the last part of the aforementioned FHWA-sponsored study because of lack of sufficient test samples.<sup>8</sup> Then in 1998, responding to the need for a commercial reinforcing bar that is corrosion resistant and yet economical, a new clad bar was introduced in the United States by Stelax Industries Ltd., of West Glamorgan, United Kingdom (Figure 1). Following the recommendation of the FHWA’s Office of Infrastructure Research and Development, representatives from Stelax visited several key state transportation agencies, including the Virginia Department of Transportation (VDOT), to introduce their new clad bars.

Stelax produces clad bars under the trade name NUOVINOX bars. The manufacturing processes begin with the processing of two materials: one for the cladding and another for the carbon steel core. For making the cladding, a flat-coiled, hot-rolled strip of 316L austenitic stainless steel is used. If desired, one of the other stainless steels, such as 304, 316, or 2205, can be used as the material for the cladding. This strip of 316L stainless steel is passed through a



**Figure 1. Earlier Samples of Stainless Steel-Clad Bars Provided by Stelax Industries Ltd., West Glamorgan, U.K. (thickness of cladding over carbon steel core varied from 5 to 10 mm).**

mill where it is formed into a pipe, and then its sides are welded together by plasma. This stainless steel pipe is about 100 to 115 mm (3.9 to 4.5 in) in diameter and has a wall 6 to 9 mm (0.24 to 0.35 in) thick. For the core of the clad bars, carbon steel shavings are used. These are processed into fine granulates, which are cleaned and then inserted incrementally (together with a reducing powder) into the heavy-walled stainless steel pipe and repeatedly compacted tight (until refusal) by a hydraulic ram. The compacted composite pipe is heated in a furnace up to 1250°C (2,280°F), in a reducing atmosphere (to prevent formation of oxides on the carbon steel granules and the inner wall of the pipe), and then hot rolled 10 times into clad bars of the right size. This hot rolling creates a metallurgical bond of approximately 5 microns (0.0002 in) in the interface between the core and the cladding, with bond strength of approximately 280 MPa (40 ksi). The final step is the acid pickling of the bars to eliminate scales resulting from the rolling process and to initiate the formation of chromium oxide on the surface of the bars, which enhances corrosion resistance. The thickness of the cladding is typically 0.9 to 1.8 mm (35 to 70 mil) for a bar diameter of 15.9 to 32.3 mm (0.62 to 1.27 in).

When the stainless steel cladding is compared with the epoxy coating on epoxy-coated bars, the differences are significant. The epoxy coating is typically 0.25 mm (10 mil) thick and can be easily damaged by contact with sharp objects and impact by hard objects; in contrast, the stainless steel cladding is several times thicker than the epoxy coating and is much tougher. Electron micrographs of cross sections of the clad bars showed the cladding fused into the outer layer of the black steel core to form a strong interface.

Since the carbon steel shaving comprise a low-cost by-product from other industries and represent approximately 77 percent by weight of the clad bars and the stainless steel clad is the remainder, the cost of manufacturing this clad bar is sufficiently economical for its price to be low. The mill price for stainless steel 316L-clad bars was \$1.32/kg (\$0.60/lb), which is about

one third the cost of solid stainless steel bars. Including all other costs, such as fabrication, duty, freight, bond fees, installation, etc., the estimated installed cost is approximately \$2.20/kg (\$1.00/lb). Upon request, Stelax could provide bars with cladding made of 304L or 3Cr12 at \$0.22/kg (\$0.10/lb) or \$0.44/kg (0.20/lb), respectively, less than with 316L cladding.

With such a relatively low price and a corrosion resistance that is probably as good as that of solid stainless steel bars, clad bars have the potential of becoming the cost-effective reinforcing bars that can delay corrosion in concrete bridges and thereby enable these structures to achieve a serviced life of 75 to 100 years (without any major repair necessitated by bar corrosion). However, corrosion data and field experience for clad bars were limited.

## **PURPOSE AND SCOPE**

To contribute toward filling this gap and possibly help clear the way for the wide use of stainless steel-clad bars, Virginia recently initiated a research program that was aimed at (1) verifying the good corrosion resistance of clad bars alluded to by the earlier studies,<sup>6,7</sup> and (2) trying out these bars in the construction of a new concrete bridge deck as part of the FHWA's Innovative Bridge Research and Construction Program.

### **LABORATORY EVALUATION OF CORROSION RESISTANCE OF 316L STAINLESS STEEL-CLAD BARS**

In 2000, a research project was initiated at the Virginia Transportation Research Council (VTRC), with the assistance of the Materials Science Department of the University of Virginia, to determine the chloride corrosion threshold of the Nuovinox clad bars.<sup>9,10</sup> This assessment was conducted using salt-exposed concrete and solutions with different chloride contents and pH values separately as the test media. The test concrete blocks were intended to provide a realistic simulation of the environment that typically surrounds reinforcing bars embedded in concrete bridges, wherein the concentration of chloride ions typically start at nil and then slowly builds up. In contrast, with the solutions, the bars are almost immediately exposed to the chloride ions. In addition, because the electrical conductivities of the solutions are typically higher than that of concrete, a harsh, or worst-case, test environment was provided. Therefore, the test in solutions was aimed at ensuring that the chloride corrosion thresholds for the different bars can be determined, just in case the accompanying test in the concrete blocks failed to do so within the limited duration of the study.

For testing in concrete, the clad bars were embedded in concrete blocks made of a mix design with a high water-to-cement ratio of 0.50. The concrete blocks were then set outdoors and subjected to weekly cycles of ponding for 3 days with a saturated solution of sodium chloride followed by drying for 4 days. To pinpoint the exposure time at which the clad bars begin to corrode as a result of chloride in the concrete reaching the corrosion threshold level, the macrocell current (flowing between the top and bottom clad bars in the concrete blocks) and the

open-circuit potential of the top clad bars were monitored weekly. For comparison, bars made completely of carbon steel and 304 and 316LN austenitic stainless steels were also subjected to the same testing.

The most recent data, which correspond to 1,050 days of this severe exposure of the concrete blocks to salt, showed that the clad bars, just like the three solid stainless steel bars, still remained passive. Based on determination of the chloride contents of several randomly selected concrete blocks at several exposure times, it is estimated that the mean chloride content in the concrete blocks at this time would be  $0.5990 \pm 0.0100$  percent (by weight of concrete) at the depth of the bars. This means that these bars, including the clad bars, have been able to withstand very high levels of chloride ions in the concrete without corroding and that their “final” chloride corrosion threshold must be greater than this amount. On the other hand, the conventional black bars began to show signs of corrosion, as manifested by a rapid increase in macrocell current and negative shift in potential, as early as only 90 to 95 days of the severe salt exposure. The estimated mean chloride content for that exposure time was only between 0.0430 and 0.0580 percent, which is in agreement with the corrosion threshold level generally accepted for black bars. Up to this point in concrete, the stainless steel clad bars were as corrosion resistant as the two solid stainless steel bars (made of 304 and 316LN) and have, so far, withstood 10.3 to 13.0 times amount of chloride as the black bars did. Since the test is still in progress, it is certain that the final chloride corrosion threshold of the clad bars will be considerably higher than this.

The results of the solution tests supported this finding in that the clad bars exhibited the same high corrosion resistance as the solid 316LN stainless steel bars—the only solid stainless steel bar included in those solution tests. The tests indicated that both bars exhibited the same electrochemical properties, such as open-circuit potentials, E-vs.-log (i) function, and pit-repassivation potentials. However, in terms of the chloride corrosion thresholds in the solutions, those of the clad bars and the 316LN bars were at least 16 and 24 times, respectively, that of the black bars—with the slight difference in the corrosion resistance attributed to likely differences in the alloy compositions of the stainless steel cladding and the 316LN.

The corrosion threshold level of clad bars in concrete arrived at so far in the Virginia laboratory investigation is in good agreement with those reported earlier by other investigators for solid 304 and 316 stainless steel bars but considerably less than the greater than 24 times reported for 304 clad bar by Rasheeduzzafar et al. (see Table 1). The disagreements in the reported corrosion thresholds may be due to differences in the testing methods used. Regardless, these differences would not matter because, as will be demonstrated later, using the low-permeability concrete and the thick 70-mm (2.75-in) concrete cover that Virginia specifies for its new concrete bridge decks, a corrosion threshold of 10 times that of black steel bars would be more than sufficient to ensure that there will be no corrosion in the first 100 years life of a new bridge deck.

**Table 1. Earlier Estimates of Chloride Corrosion Thresholds for Some Metallic Reinforcing Bars Relative to Black Bars**

Investigation	Metallic Bar		
	304	316	304 Clad
Zoob et al., 1985 <sup>2</sup>	7 to 10X		
Sorensen et al., 1990 <sup>11</sup>	>10X	>10X	
Rasheeduzzafar et al., 1992 <sup>6</sup>			>24X
Nurnburger et al., 1993 <sup>12</sup>	>12X	>12X	

At this time, the concrete blocks embedded with the clad bars and the two solid stainless steel bars, and two other new bars made of new alloys (2101 LDX and MMFX-2), are continuously being subjected to the weekly salt-exposure cycles. This regime will be continued for each type of bar until the bar begins to show signs of corrosion, after which the concrete blocks will be broken to allow for examination of the bar.

### **TRIAL APPLICATION OF NUOVINOX CLAD BARS IN A BRIDGE DECK**

Initially, the concrete deck of the new westbound bridge (B623) on the relocated Route 460 over the Route 29 Bypass in Campbell County, Virginia, was selected for testing the stainless steel-clad bars. This bridge was chosen because it has a twin eastbound structure (B612), which will use epoxy-coated bars and would therefore be ideal for comparison of long-term performances.

#### **Specifications for Stainless Steel-Clad Reinforcing Bars**

There were no standards available for this type of composite bar from either the American Society for Testing and Materials (ASTM) or the American Association of State Highway & Transportation Officials (AASHTO). Therefore, temporary specifications (see the Appendix) were prepared for this trial—incorporating VDOT’s basic requirement that a reinforcing bar have a minimum yield strength of 420 MPa (60 ksi) and also many of the requirements specified for deformed bars in ASTM A615, Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement. The most important requirements in the temporary specifications were the ones regarding the strength, type, and thickness of cladding; deformation on the bars; bending; and sealing of the bar ends.

#### **Problems Encountered with Delivery of Clad Bars by Stelax**

For the entirety of the deck on B623, which has a total surface area of 2,879 m<sup>2</sup> (30,993 m<sup>2</sup>), 98,901 kg (218,040 lb) of Grade 60 clad bars was ordered from Stelax in fall 2000. By late February 2002, when the contractor was ready to install reinforcing bars and then place concrete

on the deck, only approximately 20 percent of the ordered bars had been delivered. This delay in bar delivery and the subsequent placement of Stelax in receivership necessitated changes in the plans. After consultation with the bridge engineers in VDOT's Lynchburg District, the research team decided that the delivered clad bars would be used in Span A of B635, and epoxy-coated bars would be used in the remaining spans (B, C, and D). This combination would provide for an opportunity to compare the long-term durability of these two types of bars. The construction of the deck of B635 took place in fall 2002.

### Examination and Use of Delivered Clad Bars

Some properties of the delivered clad bars, which were all straight, were tested. As indicated in Table 2, the tensile and yield strengths exceeded the requirements for Grade 60 bars, which are 620 MPa and 420 MPa, respectively. Similar tests conducted by several other state DOTs yielded average tensile strengths from 686 to 795 MPa and average yield strengths from 439 to 484 MPa.

**Table 2. Properties of Delivered Clad Bars**

Bar Designation No. (mm)	5 (16)	6 (19)
Grade	60	60
% of Nominal Weight	110.4	103.7
Tensile Strength, MPa (ksi)	816 (118)	773 (112)
Yield Strength, MPa (ksi)	469 (68.0)	461 (66.8)
Elongation (%)	17	11

In terms of the spacing, height, and pattern of the deformations (ribs), the clad bars complied with all of the requirements of ASTM A-615. However, the deformations were somewhat smoother and, therefore may be considered less desirable than those in the sample bars provided earlier by Stelax (Figure 2).



**Figure 2. Deformations on Section of One Delivered Clad Bar (Top) and Sample Clad Bar Provided Earlier by Stelax (bottom).**

To determine the average thickness of the cladding, 24 pieces of the No. 6 clad bars were randomly selected. Then, at one end of each of these bars, the thickness of the cladding was measured at two points: (a) at one of the two longitudinal deformations, and (b) at a midpoint between two ribs. The results, which are summarized in Table 3, indicated that the cladding tended to be thicker at Point (a) than at Point (b), as illustrated clearly in Figure 3. The minimum cladding thickness was 0.6 mm, which is greater than the arbitrarily specified minimum of 0.5 mm.

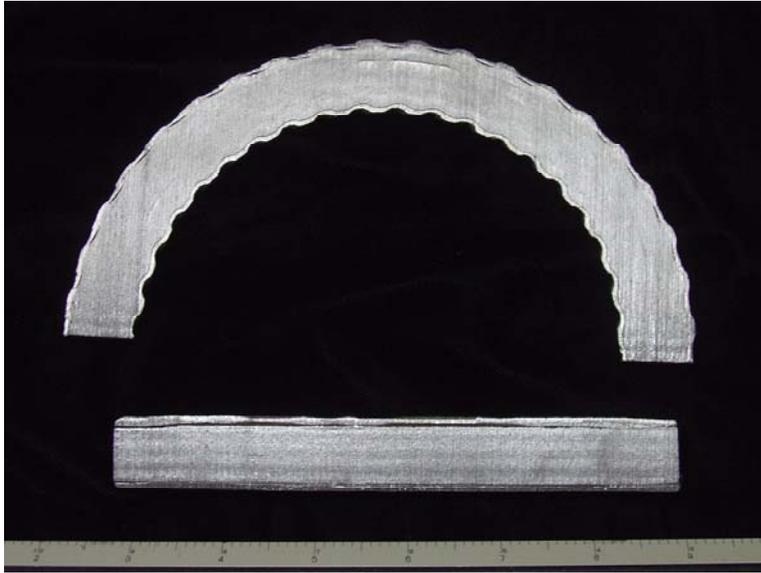
**Table 3. Thickness of Cladding on No. 6 Clad**

<b>Thickness (mm)</b>	<b>Point (a)</b>	<b>Point (b)</b>
Mean	3.7	0.9
Standard Deviation	0.7	0.2
Minimum	2.2	0.6
Maximum	4.6	1.2

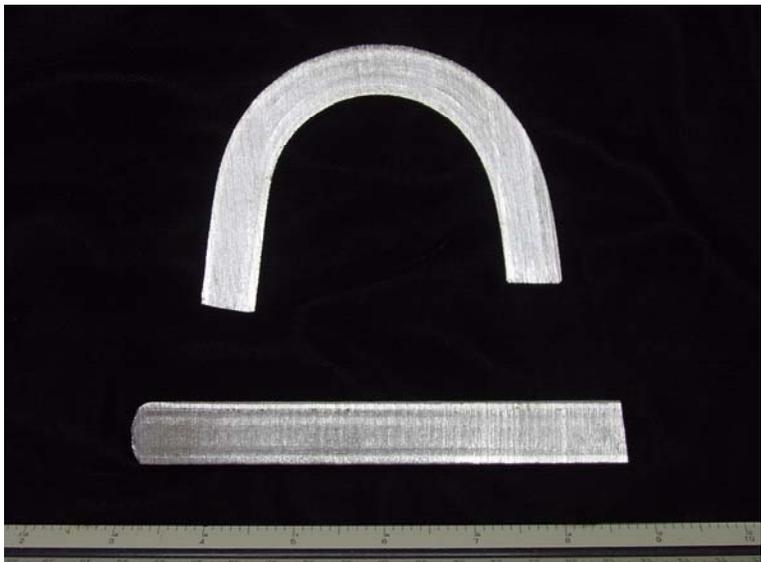


**Figure 3. Ends of Some Stainless Steel Clad Bars**

A concern with clad bars is that if during the manufacturing the super-heated composites of stainless steel pipes (filled with compacted carbon steel granules) are not rolled properly, the cladding could disbond from the core—especially when the clad bars are bent. This problem was encountered with some of the clad bars delivered to a transportation agency in fall 1999, which were part of the first batch of commercial clad bars that came out of the Stelax plant (Figure 4). In some bars, there were already disbondments between the cladding and the core even before the bars were bent; in addition, the stretching that occurs at the outer portion of a bar during bending had a tendency to concentrate the disbonding at the valleys between the ribs. To ascertain that the clad bars received in this project had good bonding between the cladding and the core, several test samples were taken from the shipment and were sliced longitudinally in half—with and without 180° bending first (using the pin diameter required in ASTM A615). All the sliced samples showed good bonding between the cladding and the core, indicating that the initial problem encountered by Stelax during the hot rolling process had been eliminated. Figure 5 shows some of the slices.



**Figure 4. Disbonding Between Stainless Steel Cladding and Carbon Steel Core in Earlier Bars.**



**Figure 5. Slices of Delivered Clad Bars Before and After Bending (notice improved bonding between cladding and core).**

An aspect of the delivered clad bars that was not completely satisfactory was the sealing of the ends. For this shipment, Stelax used plastic caps instead of the specified liquid two-part epoxy mix. As Figure 6 shows, such plastic caps can become detached from the ends—even when glued to the bar ends with an adhesive.

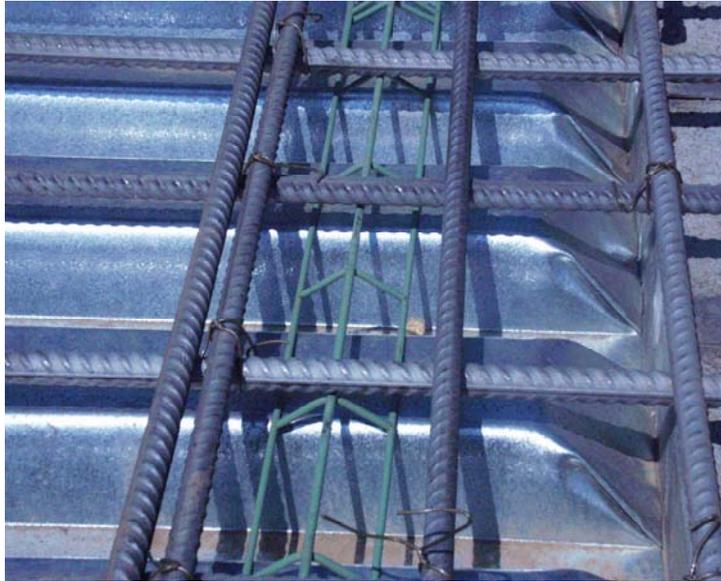


**Figure 6. Ends of Clad Bars Covered with Plastic Caps (notice slight corrosion on exposed core of one bar where cap became loose).**

Figures 7 and 8 show clad bars in place in sections of Span A of the bridge structure. Since the length of the clad bars ranged from only 5.6 to 9.7 m (18.4 to 81.8 ft), with the maximum length limited by the typical size of containers used in trans-oceanic shipping, alternating lap splices of bars were necessary in many places. Because of the toughness of the cladding, no cracks or other form of damage on the cladding of the installed bars was visually observed. Thus, it is expected that the cladding will provide very good protection to the bars against corrosion.



**Figure 7. 316L Stainless Steel Clad Bars in Span A of B635.**



**Figure 8. Closeup of Clad Bars Near Girder (notice use of epoxy-coated chairs).**

In contrast, damage to the epoxy coating was easily observed on many of the epoxy-coated bars installed on the other spans (Figures 9 and 10)—especially over the ribs—despite their good condition before placement (Figure 11). Such damage typically occurs when a sole construction worker attempts to bring the bars, which can be as long as 18 m (60 ft), from a storage area (typically located at one end of the bridge being constructed) to a span for placement by dragging the bars over other bars already in place. Such a practice leads invariably to severe abrasion damage to the coating of the bars being transferred and those that are already in place, particularly at the high points of the bars—the ribs.



**Figure 9. Epoxy-Coated Bars Used in Other Spans of B635 (notice damage on epoxy coating over ribs of bar in middle).**



**Figure 10. Coating Damage on Epoxy-Coated Bar.**



**Figure 11. Epoxy-Coated Bars at Storage Area in Construction Site of B635 (notice condition of epoxy coating was still good).**

It is suspected that additional damage may have been introduced to the coating during the placement and consolidation of the concrete. No attempt was made to determine the extent of such damage in this particular construction project, simply because there was no practical way to do so without disturbing the concrete. However, a reported study of the construction of several bridge decks in a midwestern state may provide an indication of the possible extent of this type of coating damage. It was observed that the average coating damage increased from 8.1 defects/m of bars before concrete placement to 30.8 defects/m after placement—a 280-percent

increase in coating damage which the investigators attributed to concrete pumping operation.<sup>13</sup> This type of coating damage can, of course, vary from construction project to project, since it is dependent on such variables as the shape of the coarse aggregates, the height and rate with which the concrete is discharged and impacts the bars, the thickness of the epoxy coating, and the manner in which the concrete is consolidated.

Table 4 lists the mix design used for building the deck. As testing of concrete samples shows, this mix design yielded a concrete with good strength and low permeability. The construction of the deck was completed in November 2002.

**Table 4. Concrete Mix Design Used for B635**

Cement (kg)	144
Slag (kg)	144
Sand (kg)	534
Coarse Aggregates (kg)	873
Water (kg)	130
Air Entrainment (ml)	60 to 300
Retarder (ml)	560 to 740
Water Reducer (ml)	0 to 470
w/(c + m)	0.45
Slump (mm)	114
Air (%)	6.25
Compressive Strength (MPa) at 28 days	45.4
Permeability (Coulomb) at 28 days	1,450

### **COST-EFFECTIVENESS ANALYSIS**

Cost will always be a factor in the acceptance of a new material. Potential users will, it is hoped, rightfully give more emphasis to long-term cost than initial cost when selecting a bar. The bid price of these clad bars was \$2.54/kg (\$1.15/lb), installed, which was approximately \$0.26/kg (\$0.12/lb) higher than anticipated initially—based on estimates of various costs, such as cost at mill, duty and freight, port fees, fabrication, etc. As expected, this initial cost was higher than the current average market prices of uncoated black steel bars and the widely used epoxy-coated black steel bars (see Table 5). In terms of the overall cost of a bridge construction project, however, the additional cost for switching from the current specified coated bars to clad bars is expected to be small. Using this project as an example, the use of the clad bars would cost only an additional 4.2 percent of construction funds over the total cost of the structure with epoxy-coated bars (see Table 5).

**Table 5. Additional Initial Cost for Using Clad Bars Instead of Epoxy-Coated Bars**

<b>Cost Description</b>	<b>ECR</b>	<b>Clad Bars</b>
Cost of Structure B635	\$903,760	\$942,000
Amount of Bars Required for Deck	31,539 kg	31,539 kg
Unit Price of Bars (installed)	\$1.32/kg	2.54/kg
Total Cost of Bars	\$41,720	\$79,960
Cost Differential for Bars	0	\$ 38,240
Cost Differential for Bars as Percentage of Structure Cost	0%	4.2%

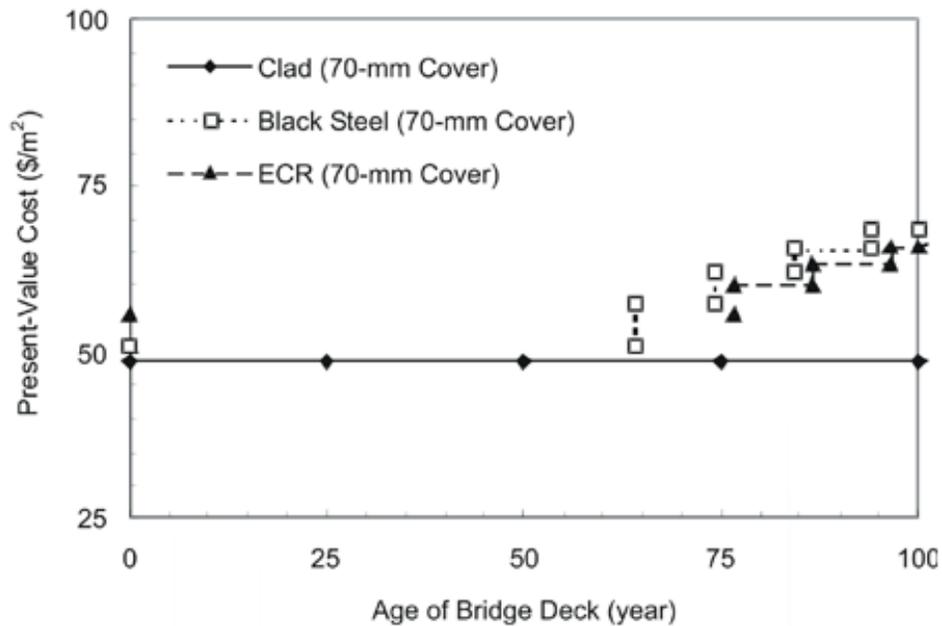
To make a rational decision on which type of bar to use in a concrete structure that will be subjected to harsh salt exposure during winters would require that the differential in capital costs also be viewed from the standpoint of long-term costs for the different options—taking into consideration that the use of a corrosion-resistant bar will lead to a reduction in the frequency, or even elimination, of repairs that would otherwise be necessitated by bar corrosion.

The long-term, or life-cycle, cost of using either of these three different bars in this deck can be estimated based on the initial costs of the bars and concrete, an assumed discounted future repair cost over 100 years, and the “typical” salt exposure environment for Roanoke, Virginia, the location closest to Lynchburg for which such historical weather data are available (Table 6). The chloride corrosion thresholds used for uncoated black steel and clad bars were those determined in the laboratory phase of this investigation and discussed earlier. As is common practice, the corrosion threshold of epoxy-coated bars was assumed to be equivalent to that of the uncoated bars. However, the model used in this exercise to estimate various life-cycle costs, Life-365, accounts for the beneficial effect of the epoxy coating by increasing the corrosion propagation period from 6 years (assumed for uncoated bars) to 20 years for the coated bars.<sup>14</sup>

The changes with age of the deck of the predicted life-cycle costs are illustrated in Figure 12 for the design concrete cover of 70 mm. As shown, it is estimated that the present-value cost of the bridge deck using clad bars will remain constant at \$48.60/m<sup>2</sup> throughout the first 100 years of the bridge deck—actually for a much longer time. This is less than the estimated costs of using the two cheaper bars, which are \$50.75/m<sup>2</sup> during the first 64 years for uncoated black steel bars and \$55.50 /m<sup>2</sup> during the first 76 years for epoxy-coated black steel bars. The model predicted that as sufficient chloride ions accumulate in the concrete surrounding the top-mat bars to induce corrosion, and given time for corrosion to propagate, the deck will begin to require repairs after approximately 64 years for uncoated and 76 years for the coated black steel bars—with the difference arising from the different corrosion propagation periods of these two bars. At year 64, the cost for the deck built with black steel bars surpasses the costs for the other two bars. It is also predicted that the cost for using either black steel or epoxy-coated bars will continue to rise incrementally at every repair interval, which, in this exercise, was set at 10 years—the model’s default value.

**Table 6. Parameters Used for Estimating Long-Term Costs Associated with Using Different Bars in Deck of Structure B635**

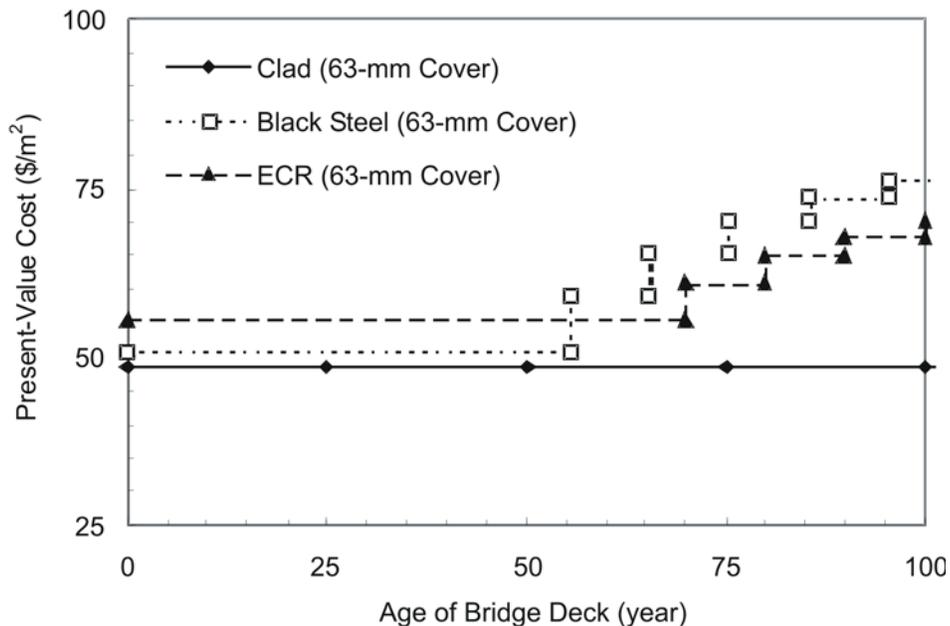
<b>Dimension of Concrete Deck</b>	
Overall thickness	230 mm (9.0 in)
Clear concrete cover	70 mm (2.75 in)
<b>Base Concrete Mix Design</b>	
w/(c + m)	0.45
Slag content	50%
Chloride diffusion constant (at 28 days)	$1.05 \times 10^{-11} \text{ m}^2/\text{s}$
Mix cost	\$118/m <sup>3</sup> (\$90.00/yd <sup>3</sup> )
<b>Bar</b>	
Percentage	1.2
Installed cost of bars	
Black steel	\$1.10/kg (\$0.50/lb)
Epoxy coated	\$1.32/kg (\$0.60/lb)
316 stainless steel clad	\$2.54/kg (\$1.15/lb)
<b>Other Cost Information</b>	
Repair cost	\$431/m <sup>2</sup> (\$360/yd <sup>2</sup> )
Area to repair	10% of total area
Repair interval	10 years
Discount rate	3.0%
<b>Chloride Corrosion Threshold</b>	
Black steel	0.052% (by wt. conc.)
Epoxy coated	0.052%
316 stainless steel clad	0.600%



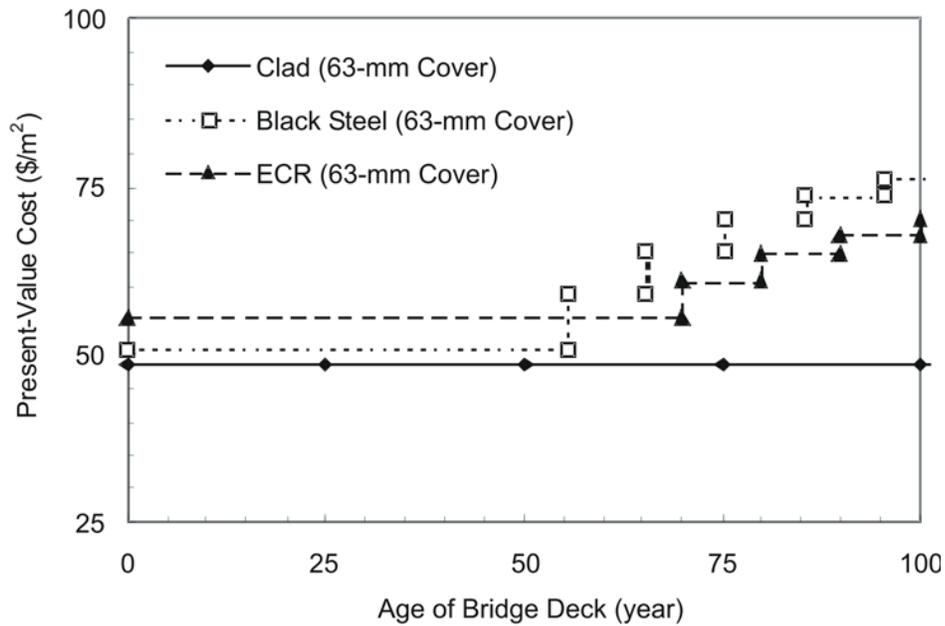
**Figure 12. Present-Value Costs of Concrete Bridge Deck on Structure B635 for Three Different Bars and Design Concrete Cover of 70 mm.**

Because of concrete cracking, it is not uncommon for concrete bridge decks in Virginia to require an overlay in approximately 20 to 25 years and, if the deck is built with uncoated black steel bars, replacement in another 25 to 30 years. Based on this experience, the predictions of 64 years before first repair for uncoated black steel bars and 76 years for coated bars may be somewhat optimistic, even though the prediction is for the use of low-permeability concrete. In fact, there has been increased cracking in newly constructed concrete bridge decks in the second half of the 1990s, especially those built with this type of concrete. Life-365 does not have the capability to model directly the effect of presence of cracks in the concrete on the time-to-accumulation of the amount of chloride required to initiate corrosion on any type of bar. This shortcoming can lead to predictions that would be too optimistic for less corrosion-resistant bars, which would be adversely affected by the presence of cracks and the resulting quick buildup of chloride in the concrete. In addition, when the cracks are caused by thermal and/or drying shrinkage after the concrete has hardened, some of these can be full-depth cracks.

As part of the exercise, the effect of the presence of cracks in the concrete was indirectly modeled, in a simplistic manner, by assuming that the cracks reduce the average effective concrete cover over the bars. As Figures 13 and 14 show, if clad bars are used, the reduction in the effective concrete cover, even by as much as 25 mm (1 in) or even greater, has no effect on the long-term cost of the deck through the first 100 years (actually for at least another 25 years). This, of course, is because the clad bars can withstand so much chloride that even with the more rapid accumulation of chloride in the thinner concrete, its concentration would still not reach the amount necessary to initiate corrosion—even in 125 years. In contrast, for decks with uncoated black steel bars, the time-to-first-repair decreases from 64 years to 55 and 49 years, respectively,



**Figure 13. Present-Value Costs of Concrete Bridge Deck on Structure B635 for Three Different Bars and Concrete Cover of 63 mm.**



**Figure 14. Present-Value Costs of Concrete Bridge Deck on Structure B635 with Concrete Cover of 44 mm for Clad Bars and 57 mm for Black Steel and Epoxy-Coated Bars.**

for a loss of cover of 6.5 and 13 mm, respectively. If epoxy-coated bars are used, the time-to-first-repair of the deck decreases from 76 to 70 and 63 years, respectively, for a loss of cover of 6.5 and 13 mm, respectively. Beyond any doubt, these results show that, among the three bars compared, only clad bars could likely provide long-term stability in the condition of the deck and its cost.

## DISCUSSION

The analysis of the long-term costs of the bridge deck showed that with an additional capital expenditure of only 4.2 percent, in the total cost of the bridge—to switch from epoxy-coated bars to clad bars—future repair work arising from bar corrosion on this project will not be necessary, in its first 100 to 125 years life; therefore, significantly reducing the life-cycle cost of the bridge deck. This is, of course, made possible by the considerably high corrosion resistance of the clad bars tested which, within the time frame of the laboratory testing that accompanies this construction project, is practically equivalent to that of the higher-cost solid stainless steel bars.<sup>9,10</sup>

Shortly after the initiation of this project, some members of the research team who had observed the Nuovinox manufacturing processes had concerns. These were the possibility of (1) inadequate or non-uniform compaction of the charges of carbon steel granules and therefore the bonding between the charges that would make up the core, and (2) poor or inconsistent bonding between the core and the cladding. As mentioned earlier, the second problem was encountered in the first production of the Nuovinox clad bars. Unfortunately, many of those defective clad bars were shipped to and rejected by a North American transportation agency, and subsequently

replaced by the manufacturer. Subsequent adjustments made to the hot rolling process had eliminated this problem in their subsequent productions, including the clad bars received in this project. Regarding possible poor cohesion between the carbon steel granules, this had never been reported by any of the other states and was not observed on any of the bars that were examined in this project.

The issue with sealing the ends of clad bars, although relatively minor, has been examined to some extent in laboratory testing in solutions;<sup>10</sup> however, it needs to be investigated further. Use of the liquid two-part epoxy mix specified in this project to seal the ends can be very effective, although it could be slightly time-consuming unless a mechanized method to carry it out is devised. Other options, such as using stainless steel or polymeric caps in conjunction with an epoxy sealer, welding with a stainless steel, etc., need to be evaluated.

The only significant problem experienced in this project with the clad bars was more of a business nature than technical—with the U.K. company, which was the sole manufacturer, declaring bankruptcy in the middle of this project and therefore failing to deliver the entire order. In view of the recession the world steel industry is in, this was perhaps not surprising. There is, however, an unconfirmed report that the company has already reorganized and, to overcome the “Buy U.S.” restriction on the import of foreign steel, is making arrangements with some U.S. mills to produce these particular clad bars in the United States.

Fortunately, in response to the potential market for corrosion-resistant bars, a major U.S. steel bar manufacturer (SMI-Texas) has just completed a mill to produce its own clad bars using a different process—the Osprey process, which basically involves depositing molten metal onto solid steel. Briefly, round carbon steel billets, 152 mm (6 in) in diameter and 10 m (33 ft) long, that comply with the requirements of ASTM A615, Grade 60, are grit blasted, to remove any scale and surface impurities and to prepare the surface. Then, each cleaned billet is slowly rotated and heated by a 3-Mw induction heater to reach 1100°C (2,000°F). Meanwhile, 316 stainless steel is melted at 1650°C (3,000°F) in a 5-ton induction furnace, transferred to a ladle, and then poured into an atomizing chamber. The heated billet then enters the atomizing chamber where it is coated with a fine spray created by blasting the molten stainless steel with nitrogen gas. The spray forms a 5-mm (0.2-in) stainless steel coating on the carbon steel billets—with a metallurgical bond between these two materials. The clad billets are then passed out of the spray chamber onto a cooling bed, transferred to a rolling mill where they are hot rolled into bars of different sizes and clad thickness, and then shot blasted. By using steel billets that are produced in a normal steel mill environment, in contrast to the steel granules used in the Nuovinox processes, the quality and homogeneity of the carbon steel core in this clad bar are likely to be better. However, this process consumes a relatively high amount of energy and also entails some material loss—both of which can adversely affect the competitiveness of the price of this particular clad bar.

Interestingly, within a period of 18 to 24 months after the introduction of the Nuovinox clad bars, three other bars were introduced to the market. Two of these bars, the MMFX-2 microcomposite and the 2101 LDX, are made of new alloys. The third, an experimental epoxy-coated bar made available to VTRC for testing, is a black steel bar that is first sprayed with a 2-mil layer of zinc and then coated with epoxy. It is intended for the layer of zinc to protect the

steel galvanically wherever there is damage in the epoxy coating. These bars have already undergone testing at VTRC in salt-exposed concrete blocks for 2 years and, so far, the results for some of these bars have been very encouraging. Therefore, at least one of the two new-alloy bars will be used in a new concrete decks, as another project funded by FHWA's Innovative Bridge Research and Construction Program.

## **CONCLUSIONS**

- Stainless steel-clad bars can be used as direct substitutes for either uncoated black steel or epoxy-coated bars for effective, corrosion-resistant reinforcement of concrete bridge decks that will be exposed to deicing salts.
- The long-term costs of such structures will be less than those built with either black steel or epoxy-coated bars, which have lower initial costs. This advantage of clad bars becomes more attractive as the expected service life of the structures is raised.

## **RECOMMENDATIONS**

1. As soon as the supply becomes stable, stainless steel-clad bars should be considered an option for reinforcing new concrete bridges that will be part of any major urban and/or heavily traveled highways and will be exposed to heavy salting.
2. Because of their potential for providing similar savings, use of the other recently introduced bars should also be examined.

## **ACKNOWLEDGMENTS**

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## APPENDIX

### VIRGINIA DEPARTMENT OF TRANSPORTATION SPECIAL PROVISIONS FOR DEFORMED STAINLESS-STEEL CLADDED CARBON STEEL BARS FOR REINFORCEMENT OF CONCRETE DECKS (METRIC)

April 1999

#### I. DESCRIPTION

These special provisions cover deformed stainless-steel clad carbon steel bars for use in reinforcement of concrete decks exposed to conditions requiring resistance to corrosion. The bars are to be supplied by Stelax Limited, West Glamorgan, United Kingdom (Tel: 011-44-163-982-0666). The standard sizes and dimensions of deformed bars and their numerical designation shall be equivalent to those listed in Table 1 of ASTM A 615M. Unless otherwise stated below, all other aspects of the clad bars shall conform to ASTM A 615M.

The reinforcing bars shall have a core of carbon steel with a cladding of 316L austenitic stainless steel.

All reinforcing bar dimensions on the drawings are to the centers of bars, except where otherwise noted, and are subject to fabrication and construction tolerances.

#### II. PHYSICAL PROPERTIES

The clad bars shall have the following physical properties:

Minimum yield strength	420 MPa
Minimum tensile strength	620 MPa
Minimum elongation	9%

The yield point shall be determined by halt in the gage of the testing machine. In the case where the bar does not have a well-defined yield point, the yield strength shall be determined by reading the stress corresponding to the prescribed strain using the autographic diagram method or an extensometer as described in ASTM A 370. The strain shall be 0.35%.

#### III. THICKNESS OF THE CLADDING

The minimum thickness of the cladding at any portion of a bar shall be 0.50 mm. Clad bars with cladding thickness below this amount shall be replaced by the manufacturer.

#### IV. CHEMICAL COMPOSITIONS OF THE CLADDING AND THE CORE

The chemical compositions of the flat-coiled, hot-rolled strips of 316L austenitic stainless used for the cladding and the carbon steel core shall conform to ASTM A 276 and ASTM A 615M, respectively. The phosphorus content of the carbon steel core shall not exceed 0.06%.

For each batch of clad bars delivered, the manufacturer shall provide: (1) a certified analysis of the elemental composition, for each cast of the hot-rolled strips of 316L austenitic stainless, used for the cladding, and (2) a certified analysis for each batch of steel shavings/granulates used for the carbon steel core.

## **V. REQUIREMENTS FOR DEFORMATIONS**

Deformations on the clad bars shall be spaced along the bar at substantially uniform distances. The deformations on opposite sides of the bar shall be similar in size, shape, and pattern.

The deformations shall be placed with respect to the axis of the bar so that the included angle is not less than 45°. Where the line of deformations forms an included angle with the axis of the bar from 45° to 70° inclusive, the deformations shall alternatively reverse in direction on each side or those on one side shall be reversed in direction from those on the opposite side. Where the line of deformation is over 70° a reversal in direction is required.

The average spacing or distance between deformations on each side of the bar shall not exceed seven tenths of the nominal diameter of the bar.

The overall length of deformations shall be such that the gap between the ends of the opposite sides of the bar shall not exceed 12.5% of the nominal perimeter of the bar. Where the ends terminate in a longitudinal rib, the width of the longitudinal rib shall be considered the gap. Where more than two longitudinal ribs are involved, the total width of all longitudinal ribs shall not exceed 25% of the nominal perimeter of the bar. Furthermore, the summation of gaps shall not exceed 25% of the nominal perimeter of the bar. The nominal perimeter of the bar shall be 3.14 times the nominal diameter.

The spacing, height and gap of deformations shall conform to the requirements prescribed in Table 1 of ASTM A 615M.

### **Measurement of Deformations**

The average spacing of deformations shall be determined by dividing a measured length of the bar specimen by the number of individual deformations and fractional parts of deformations on any side of the bar specimen. A measured length of the bar specimen shall be considered the distance from a point on a deformation to a corresponding point on any other deformation on the same side of the bar. Spacing measurements shall not be made over a bar area containing bar marking symbols involving letters or numbers.

The average height of deformations shall be determined from measurements made on not less than two typical deformations. On each deformation, three measurements shall be made: one at the center of the overall length and the other two at the quarter points of the overall length.

Insufficient height and circumstantial coverage, or excessive spacing of deformations shall not constitute cause for rejection unless it has been clearly established by determinations on each lot (see note below) tested that typical deformation height, gap, or spacing does not conform to the minimum requirements prescribed in the previous section. No rejection may be made on the basis of measurements if fewer than ten adjacent deformations on each side of the bar are measured.

NOTE: A lot, for this purpose, is defined as all the bars contained in an individual shipping release or shipping order.

## VI. BENDING REQUIREMENTS

The bend test specimen shall withstand being bent around a pin without cracking on the outside radius of the bent portion. The requirements for degree of bending and sizes of pins are prescribed in Table 1.

The bend test shall be made on specimens of sufficient length to ensure free bending and with apparatus that provides the following:

1. Continuous and uniform application of force throughout the duration of the bending operation, and
2. Unrestricted movement of the specimen at points of contact with the apparatus and bending around a pin free to rotate, and
3. Close wrapping of the specimen around the pin during the bending operation.

**Table 1. Bend Test Requirements**

Bar Designation No.	Pin Diameter for Bent Test*		
	Grade 300	Grade 420	Grade 520
10, 13, 16	3½ d**	3½ d**	
19	5 d	5 d	5 d
22, 25	....	5 d	5 d
29, 32, 36	....	7 d	7 d
43, 57 (90°)	....	9 d	9 d

\*Test bends 180° unless noted otherwise.

\*\*d is the nominal diameter of specimen.

Other acceptable, more severe methods of bend testing, such as placing a specimen across two pins free to rotate and applying the bending force with a fixed pin, may be used. When failures occur under more severe methods, retests shall be permitted under the bend test method prescribed in 10.2 of ASTM A615M.

## **VII. Core/Cladding Bond Strength**

The core/cladding shall have nominal bond strength of 280 MPa.

## **VIII. CORROSION RESISTANCE REQUIREMENTS**

The austenitic stainless steel sheets shall be tested in accordance with Practice E of ASTM A 262.

## **IX. PROTECTION FOR THE ENDS OF CUT BARS**

The cut ends of the each bar shall be protected with an epoxy resin of adequate abrasion resistance. Any damage during shipment from manufacturing plant to construction site shall be repaired with similar resin. Use of other means of protection must be approved first by the project engineer.

## **X. REPORT**

The following information shall be reported on a per batch basis:

1. Stainless steel cladding type,
2. Chemical composition of cladding and product check (if appropriate),
3. Bar size,
4. Tensile properties,
5. Bend and bond strength test, and
6. Corrosion test.